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The Practice of Weather Forecasting

By P. G. Wickham

Modern weather forecasting is a mixture of electronic computations and human judgement. This book is concerned with the latter, and it was written mainly for young professional forecasters. However, no reader who has a modest grounding in elementary meteorology and who wishes to find out how weather maps are used in day-to-day forecasting need be deterred by it. The discussion is, throughout, entirely simple and non-mathematical and the text is copiously illustrated by weather maps.

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By R. Dixon, B.Sc. and E. A. Spackman, M.Sc.

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METEOROLOGICAL OFFICE Met.O.854

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A STUDY OF SNOWMELT FLOODS IN A MOUNTAINOUS CATCHMENT USING LIMITED METEOROLOGICAL DATA

By J. S. HOPKINS

Summary. A firm of consulting engineers required estimates of a plausible 'upper limit' to snowmelt flood discharge from a small mountainous catchment in the Elburz Mountains of northern Iran. Twenty years' daily maximum temperatures at the lower end of the catchment were analysed to derive plausible critical sequences of daily maximum temperature which were then applied to run-off/temperature relationships derived from observed snowmelt discharges.

Introduction. The catchment of the River Lar above Pulur in northern Iran has an area of about 725 km^2 and lies within the altitude range 2400 m (at Pulur) to over 5600 m (summit of Mount Demavend) — see Figure 1. The 20-year average daily maximum temperature at Pulur is below 0°C until the middle of February, and then rises to about 20°C by early June.

The rapid growth of Tehran has necessitated major water-storage projects in the Elburz Mountains[1] and a firm of British consulting engineers designing the spillway for a proposed dam just above Pulur required 'upper limits' to both snowmelt and rainfall flood discharge which could be considered feasible under the present climatic régime. This paper describes the technique adopted to compute a likely 'upper limit' to snowmelt discharge using the very limited meteorological data available.

Meteorological data available. The meteorological factors determining the rate of melt of a snow pack are :

(a) incident short-wave radiation,
(b) long-wave radiation exchange between the pack surface and the atmosphere,
(c) turbulent transfer of sensible and latent heat between the pack and the atmosphere,
(d) sensible heat gained from rain falling on the pack, and
(e) heat conduction from underlying soil.

An energy-balance equation can be constructed and measurements of long- and short-wave radiation fluxes, dry- and wet-bulb temperatures and wind speed over the snow surface inserted to compute the melt rate. In certain well-instrumented catchments, variations in snowmelt run-off have been very successfully simulated by this method.[2] The basic problem in the

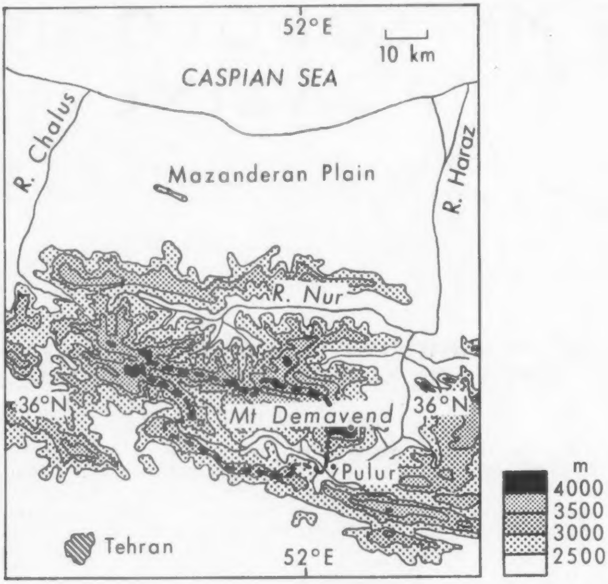

FIGURE 1—TOPOGRAPHY OF THE LAR AREA

Pecked lines denote catchment boundary.

Lar catchment was that the only meteorological variable available for any reasonable length of record was daily maximum dry-bulb temperature measured at Pulur since 1950. It was necessary to assume, therefore, that this one variable would provide a reasonable index of melt rate within the catchment (factors (a) to (d) above are undoubtedly well correlated with air temperature) and also of peak run-off from the catchment at Pulur.

Temperature/run-off relationships. Figure 2 shows the schematic snowmelt hydrograph at Pulur resulting from the diurnal variation of air temperature. The time of concentration, t, is a function of catchment size, shape, slope and soil; the depth and density of remaining snow will also affect the rate of run-off. For the Lar catchment, t is about 12 hours. Because of this reasonably short time of concentration, the peak flow Q_{max} can be separated simply into the base flow Q_b, which is the estimated flow which would have occurred without the latest flood event, and the direct run-off ΔQ. ΔQ is some function of the preceding day's maximum temperature (T_1) and Q_b some function of the maximum temperature 2 days before (T_2). A small component Q'_b could be considered a function of the maximum temperature 3 days before (T_3), but the size and water-retaining properties of the catchment are such that there is very little influence on the hydrograph 3 days after an initial event, be it rainfall or snowmelt.

To estimate the likely dependence of snowmelt rate on temperature at Pulur, an idealized catchment can be considered, as shown in Figure 3. The dimensions are :

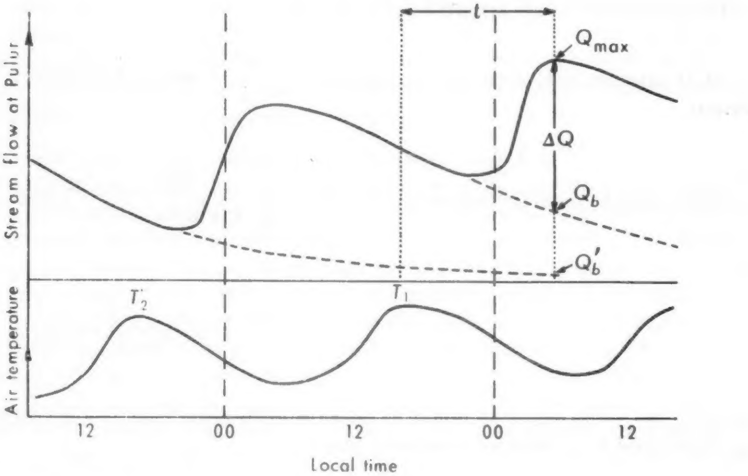

FIGURE 2—SCHEMATIC VARIATION OF AIR TEMPERATURE AND SNOWMELT RUN-OFF

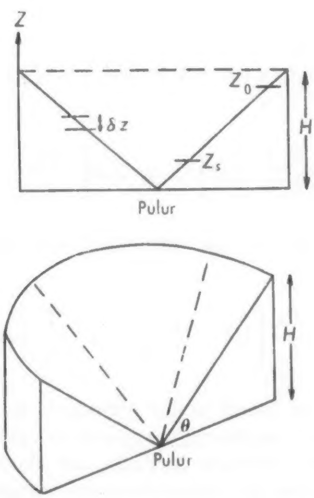

FIGURE 3—SIMPLIFIED CATCHMENT MODEL

H, the height of the watershed above Pulur
Z_s, the height of the snow-line above Pulur
Z_0, the height of the 0°C level above Pulur
δz, an element of the height variable z
and θ, the slope of the catchment.

Assume that heat transfer to the snow surface is linearly dependent on air temperature, T, alone, then :

Heat transfer $= kT$, where k is constant.

Melt rate per unit area of snow surface $= \dfrac{kT}{L}$, where L is latent heat of fusion.

$$\text{Melt rate, } R, \text{ over the whole catchment} = \int_{Z_s}^{Z_0} \frac{k\pi}{L \tan\theta.\,\sin\theta} \,.\, Tz\mathrm{d}z$$

$$= k' \int_{Z_s}^{Z_0} z(T_P - \Gamma z)\mathrm{d}z,$$

where $\Gamma = -\,\partial T/\partial z$ is assumed to be a uniform lapse rate, T_P is temperature at Pulur and k' is another constant, thus

$$R = k' \left[T_P\frac{z^2}{2} - \Gamma\frac{z^3}{3}\right]_{Z_s}^{Z_0}. \qquad \ldots (1)$$

Two cases of interest arise :

(a) The 0°C level is below the watershed, i.e. $Z_0 < H$, then $Z_0 = T_P/\Gamma$ and equation (1) reduces to :

$$R = \frac{k'}{\Gamma^2}\left[\frac{1}{6}T_P{}^3\right] - k'\,Z_s{}^2\left[\frac{T_P}{2} - \Gamma\frac{Z_s}{3}\right].$$

(b) The 0°C level is above the watershed, i.e. $Z_0 > H$, then equation (1) reduces to :

$$R = k'\,\frac{T_P}{2}\left[H^2 - Z_s{}^2\right] - k'\,\frac{\Gamma}{3}\left[H^3 - Z_s{}^3\right]. \qquad \ldots (2)$$

At the time of the year when major snowmelt floods have occurred (late April to early June), daily maximum temperatures at Pulur are such that case (b) will apply; when temperatures at Pulur are above 10°C, less than 10 per cent of the catchment area will have sub-zero temperatures, if a lapse rate of 9 degC/km is assumed. On potentially critical snowmelt occasions when there is a low snow-line (i.e. Z_s small compared with H), equation (2) indicates that the melt rate over the catchment is linearly dependent on the temperature at Pulur.

Integration of R over the time during which T_P is above zero (i.e. morning to evening) gives the total direct run-off for the day; assumption of a consistent shape of hydrograph enables the *maximum* rate of direct run-off (ΔQ) to be taken as proportional to the *total* direct run-off for the day. A similar assumption about the consistent shape of the diurnal temperature–time curve allows the daily maximum temperature at Pulur to be taken as proportional to the

time-integral of T_P. Thus, knowing from equation (2) that the instantaneous snowmelt over the catchment is linearly dependent on T_P, it can be assumed with reasonable confidence that the daily maximum temperature at Pulur provides a good index of the peak rate of snowmelt discharge on occasions when circumstances can be expected to produce 'extreme' run-off.

Observed snowmelt events. Strip-charts showing the variation of river level with time at Pulur are available since 1953, and 24 pure snowmelt flood events could be selected from this record to establish the peak snowmelt run-off/temperature relationships. Rating curves obtained from the Ministry of Water and Power, Tehran, were used to convert river level to river flow, and values of ΔQ and Q_b were extracted for each event. These values are plotted versus T_1 and T_2 in Figure 4. Such plots were attempted for each month of the snowmelt season in an attempt to take into account the variation of 'ripeness' of the snow pack through the season. However, because of the poor quality of a large number of the original river-level charts and the difficulty of obtaining pure snowmelt events (not complicated by additional rainfall run-off), the number of events on each monthly plot was insufficient to give any reasonable indication of Q/T behaviour. Accordingly, all months were combined in Figure 4.

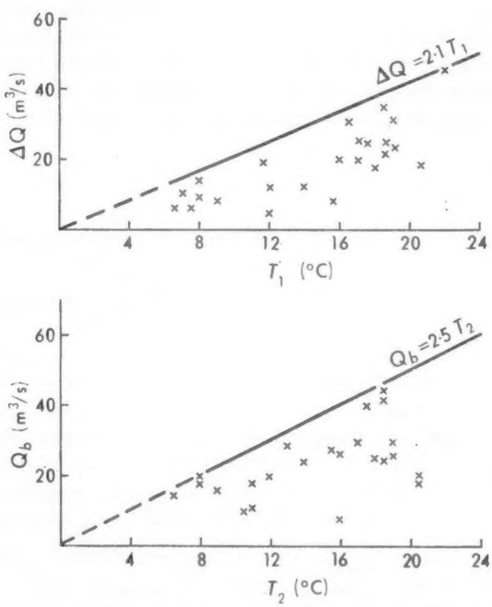

FIGURE 4—RELATIONSHIPS BETWEEN FLOOD FLOW AND PREVIOUS DAILY MAXIMUM TEMPERATURES AT PULUR

The Q/T relationship required is that which will give extreme run-off at a given air temperature when all unmeasured factors such as snow depth, snow water equivalent and height of snow-line combine critically. Such a

relationship is provided by a curve drawn to envelop a large number of Q/T observations, and following the argument set out above, there is justification in drawing the envelope as a straight line.

If the assumption of Q/T linearity can be applied over the whole range of observed T values (and there is no real evidence that this is so), then the origin on the Q/T diagram provides a reference point for the enveloping line since, when the daily maximum temperature does not attain 0°C, no snowmelt run-off should be expected.

The lines obtained are :

$$\Delta Q = 2{\cdot}1\ T_1 \qquad \ldots (3)$$

$$Q_b = 2{\cdot}5\ T_2. \qquad \ldots (4)$$

They indicate that the maximum temperature 2 days before the event has slightly more influence on the magnitude of the peak flow Q_{max} than does the maximum temperature on the day immediately preceding.

Critical temperature sequences. To obtain plausible 'extreme' temperatures for substitution into equations (3)–(4), 20 years' (1950–69) daily maximum temperatures at Pulur were collected and analysed as follows. Starting on 21 January 1950, the daily maxima over an n-day period were scrutinized, and the smallest of these maxima was selected. A similar value for each n-day period commencing 21 January of each other year of record was extracted and then the maximum of these 20 values was displayed. This value is the highest daily maximum which was attained or exceeded on each of the n days following 21 January during the 20 years of record. A simple computer programme enabled the extraction to be repeated for successive n-day periods throughout the snowmelt season and for all values for n from 1 to 6. Figure 5

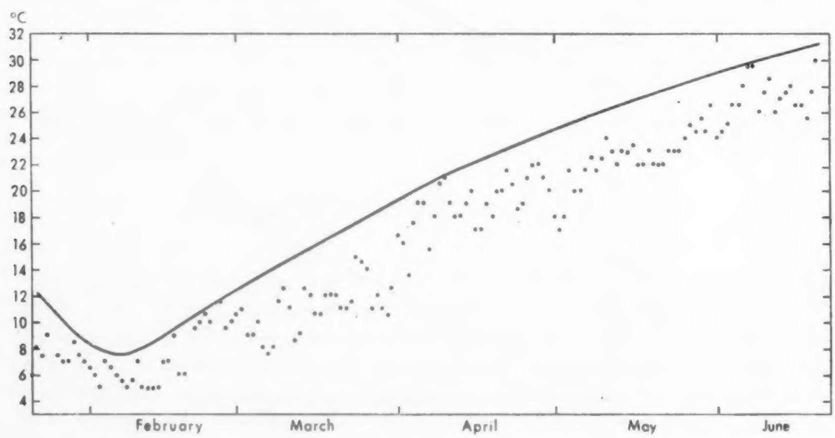

FIGURE 5—CONSTRUCTION OF EXTREME DAILY MAXIMUM TEMPERATURE CURVE FOR PULUR

$n = 2$ days

shows the temperature values obtained for 2-day periods plotted against time of year. The smooth curve drawn to envelop these observed points represents a working approximation to the 'upper limit' of daily maximum

temperatures observed over 2 consecutive days. The drawing of the envelope was, of course, subjective, but consistency was achieved by comparison with other *n*-day periods, since the 'upper limit' of temperatures on 2 consecutive days must obviously be greater than or equal to that over 3 consecutive days. Figure 6 shows the 1- to 6-day 'extreme' temperature curves, together with the 20-year-average daily maximum temperature.

Sequences of daily maximum temperatures which are likely to produce extreme snowmelt run-off and yet are not inconsistent with the temperature observations over 20 years may be constructed from Figure 6.

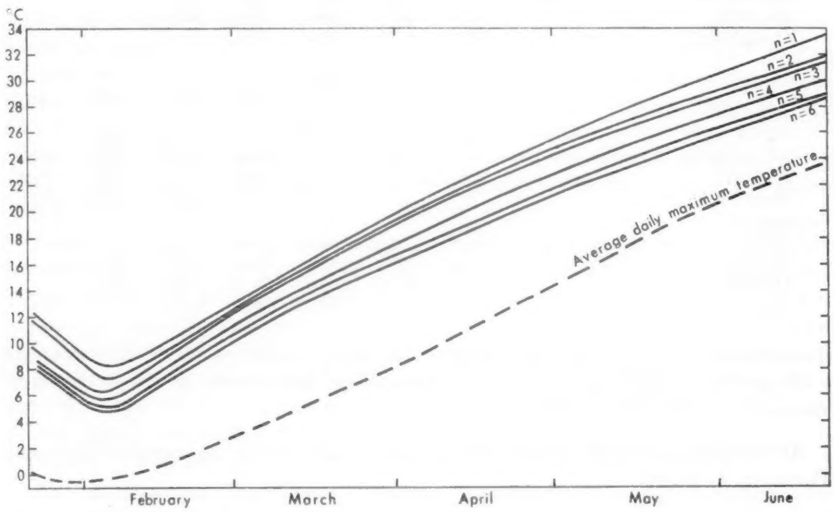

FIGURE 6—EXTREME *n*-DAY DAILY MAXIMUM TEMPERATURE CURVES FOR PULUR

Table I shows two possible sequences for early April, each assuming that 5 April has $T = 21{\cdot}0$°C, and two sequences for late May, assuming $T = 29{\cdot}6$°C on 25 May.

It is difficult to estimate how often these 'extreme' snowmelt run-off values may be attained, since the occurrence of an extreme flood event depends not only on the occurrence of high temperatures but also on the availability of a large amount of snow in the catchment. It might be considered that the early season values of Q_{max} in Table I would be approched more often than the late season values, because of the high probability of snow depletion during the course of the season.

Discussion. The demand for water-storage projects in the developing countries is likely to increase, and engineers will continue to require design figures based on physical considerations of hydrological and meteorological processes. The establishment of new climatological networks is proceeding rapidly in most countries but, until observations have been made over a number of years, the meteorologist must make the best use of the limited data which are available now. A simply based model, perhaps requiring a large number of assumptions and approximations, will often lead to a

TABLE I—EXTREME VALUES OF ΔQ, Q_b AND Q_{max} CALCULATED FROM EQUATIONS (3) AND (4) FOR TWO PERIODS DURING THE SNOWMELT SEASON

	April								
	2	3	4	5	6	7	8	9	10
Sequence 1									
T(°C)		16·7	17·4	21·0	20·4	20·0	18·6	16·8	
ΔQ(m³/s)			35·0	36·5	44·0	42·7	42·0	39·0	35·3
Q_b(m³/s)				41·7	43·5	52·5	51·0	50·0	46·5
Q_{max}(m³/s)				78·2	87·5	95·4	93·0	89·0	81·8
Sequence 2									
T(°C)	18·0	19·7	20·2	21·0	16·9	16·6			
ΔQ(m³/s)		37·8	41·3	42·4	44·0	35·5	34·8		
Q_b(m³/s)			45·0	49·2	50·4	52·5	42·2		
Q_{max}(m³/s)			86·3	91·6	94·4	88·0	77·0		

	May							
	22	23	24	25	26	27	28	29
Sequence 1								
T(°C)		24·6	26·6	29·6	28·4	28·0	25·3	
ΔQ(m³/s)			51·7	56·0	62·2	59·8	58·8	53·2
Q_b(m³/s)				61·5	66·5	74·0	71·1	70·0
Q_{max}(m³/s)				117·5	128·7	133·8	129·9	123·2
Sequence 2								
T(°C)	26·2	27·6	28·3	29·6	25·0	24·4		
ΔQ(m³/s)		55·0	58·0	59·2	62·0	52·5	51·2	
Q_b(m³/s)			65·5	69·0	70·9	74·0	62·5	
Q_{max}(m³/s)			123·5	128·2	132·9	126·5	113·7	

quantitative result which is of considerable value to the engineer, who without such guidance might be forced to 'over-design' the system in the interests of safety at considerable additional cost.

Acknowledgement. This work was performed for Sir Alexander Gibb and Partners, London.

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DESERT DEPRESSIONS OVER NORTH-EAST AFRICA

By D. E. PEDGLEY
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Summary. Desert depressions crossing north-east Africa during the spring of 1962 are described and a model developed, supported by simple physical and dynamical reasoning. A depression forms or intensifies over southern Tunisia or north-western Libya, within a surface trough extending northwards from the intertropical convergence zone, and ahead of a shallow trough in the upper westerlies where positive vorticity advection is to be expected. It moves eastward to Egypt in a lower tropospheric baroclinic zone parallel to the African coast, baroclinicity apparently being the result of differential heating on two scales — in association with the hemispheric circulation and with the land–sea contrast. It maintains a quasi-steady state and develops a well-marked cold front extending southwards from the centre along the axis of the thermal ridge in the lower troposphere.

Introduction. A characteristic feature of the weather over north-east Africa during the spring, February to June, is the occurrence of spells of

southerly winds at a time when climatological charts (e.g. Thompson[1]) show predominant directions are between north and east. These southerlies bring high temperatures and low dew-points, and sometimes they are strong enough to give widespread duststorms. This type of weather, called khamsin in the United Arab Republic (from the Arabic for 'fifty', and applied to the fifty days following the Coptic Easter) and ghibli in Libya (an Arabic word for 'south'), can cause considerable personal discomfort.

With the setting up of a synoptic network over Egypt at the beginning of this century, a relationship was soon discovered[2] between these spells of southerly winds and the approach of depressions from the west, crossing either the Mediterranean or the desert just south of the coast of north Africa. With the accumulation of synoptic analyses over a number of years it was possible to discuss [3,4] the synoptic climatology of these 'khamsin depressions'. About half of them were found to be of the 'desert' or 'Sahara' type, but the fraction was greater in April and May. Desert depressions are not frequent: an average of about six each year can be expected, the latest usually occurring about mid-June. With each depression, khamsin weather lasts a few days, rarely more than four.

Following the development of classical Norwegian ideas on the structure of depressions, frontal structures were given [5–8] to desert depressions over Egypt, but in the absence of data to the west their origin was obscure. When a synoptic network had been established over north-west Africa in the 1920s it became clear that at least some desert depressions had an origin just south of the Atlas Mountains,[9] whilst other, 'Sahara-Sudan', disturbances, developing over the sahel of West Africa south of the Sahara, in the region from Senegal to the Niger Republic, could at times be traced north-eastwards as far as Egypt.[10–12] But the nature of these latter disturbances was also obscure.

An extension of the frontal concept postulated that desert depressions formed along a front separating cool, polar air over the Mediterranean from warm air over north Africa that had come from Arabia and the Red Sea,[13] but it was later pointed out[14] that most khamsin depressions are secondaries to larger depressions over Europe or the northern Mediterranean. However, it was clear that the frontal structure was not always simple because, although the cold front is usually well marked, the warm front is frequently found to be diffuse.[15–17]

At present, although there is general acceptance of a frontal nature of desert depressions,[18–20] their structure, origin and evolution are still poorly understood, no doubt in part a result of the sparseness of data, especially from the middle and upper troposphere. A relation between surface disturbances over north Africa and waves travelling eastwards in the upper westerlies has been pointed out [21–24] and this paper attempts to extend current knowledge of this relationship, and more generally of the nature of desert depressions, by presenting the results of a study of the depressions that crossed north-eastern Africa during the spring of 1962.

Data and analyses. For the period January to June 1962, a vertical time-section was constructed for Tobruk, Libya (32° 05′N 23° 59′E, T in Figure 3), showing winds measured by radar four times each day, and temperatures measured by radiosonde twice each day. This section was used to select days on which troughs seemed to pass overhead at 500 mb, and days

on which cyclonic centres seemed to move eastwards to the south of the station. The existence of these disturbances was then checked using the working charts available in the forecast office at RAF El Adem (31° 51′N 23° 55′E), about 30 km south of Tobruk, and also the published charts in the *Daily Weather Report* of the Meteorological Department of the United Arab Republic.

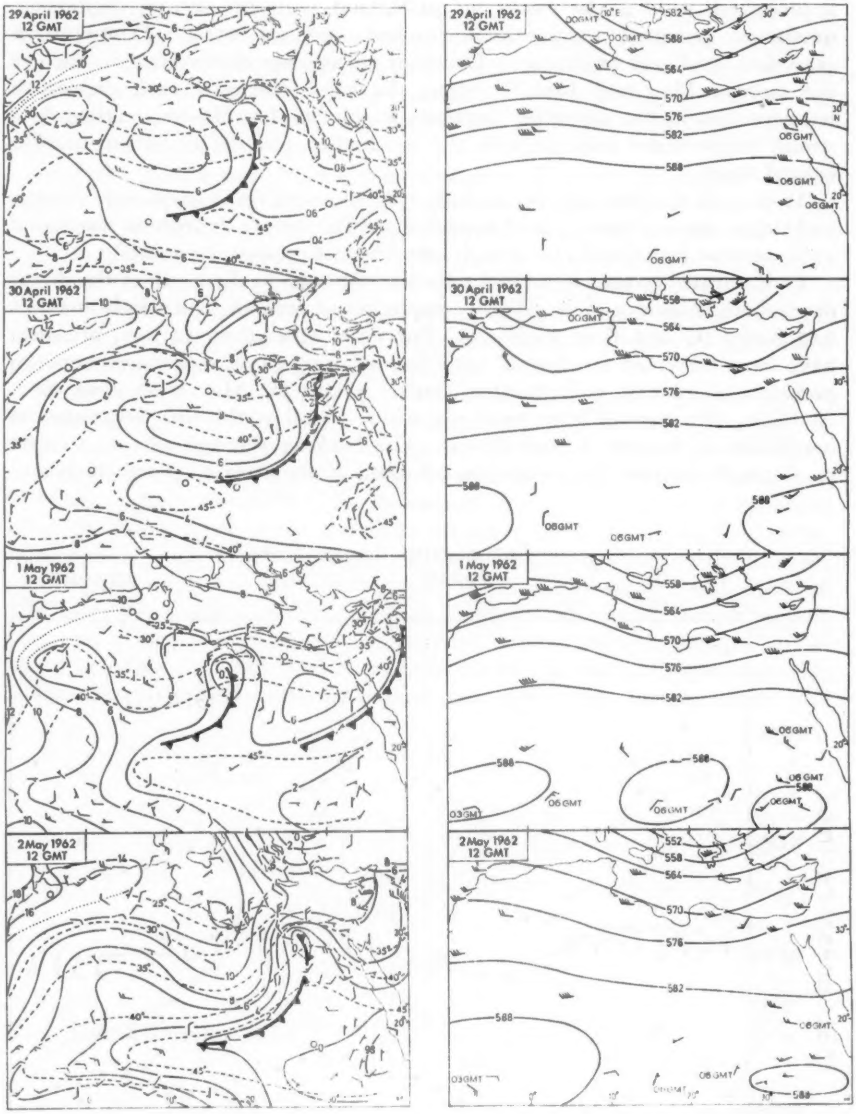
Fourteen desert depressions crossing north-eastern Africa could be discerned from the time-section during the six-month period. To study their structure, daily 12 GMT synoptic analyses were prepared for the surface and for 500 mb on a scale of 1:20 million over Africa north of the equator, the Mediterranean and Europe south of 45°N. Sufficient analyses were constructed to follow the development of each depression as it crossed north-east Africa. For such analyses, because the synoptic network is so sparse, it is desirable to have observations from the same places each day. This was possible where data were available either in published form (*Daily Weather Report* of the United Arab Republic, *Synoptic Bulletin* of the Sudan Meteorological Service, *Overseas Supplement* of the British *Daily Weather Report* and *Northern Hemisphere Data Tabulations* prepared by the National Oceanic and Atmospheric Administration) or from the original registers (in the case of Libya, data were made available by courtesy of the Libyan Meteorological Department). Elsewhere, reliance had to be placed on 12 GMT data routinely available through normal meteorological communications channels.

If only one surface chart each day is used, it is also desirable to have off-time data, at least from stations affected by disturbances, to assist in the location of centres and other synoptic features. Observations at 6-hourly intervals were available for the United Arab Republic and Sudan from the published sources quoted above, and at 3-hourly intervals for Libyan stations, except at El Adem, where hourly observations were available.

On the surface charts, winds were plotted and isobars and isopleths of potential temperature (potential isotherms) drawn. The latter were used to reduce the effects on air temperature of differences in altitude between observing stations. On the 500-mb charts, winds were plotted and contours and potential isotherms drawn. Some data for 00 or 06 GMT previous to the chart time had to be used from some stations where 12 GMT data were not available at 500 mb. This was usually on the periphery of the analysis area and never in the vicinity of a disturbance.

At both levels, disturbances lasting a few days could be tracked over distances of several thousand kilometres without much recourse to interpolation. Despite the sparse network, it was possible to draw consistent analyses on successive days without relying heavily on continuity. This success, contrasting with difficulties often encountered during routine analysis, can be attributed to the use of observation sequences which are often not available routinely.

A pair of desert depressions. Figure 1 shows a chart sequence from 29 April to 2 May 1962. During this period two depressions moved eastwards along remarkably similar tracks near 30°N, starting south of the Atlas Mountains and continuing just south of the African coast. Each had a central pressure around 1000 mb and maximum winds of 20 to 30 kt, sufficient to give spells of rising sand, or duststorms, lasting a few hours. The centres lay



(a) Surface
——— Isobars at 2-mb intervals
– – – Potential temperature (°C)

(b) 500-mb contours
——— Contours (geopotential decametres)

FIGURE 1—SEQUENCES OF 12 GMT CHARTS FOR THE PERIOD 29 APRIL TO 2 MAY 1962

International symbols are used for plotting the winds.

at the northern limits of troughs extending from the intertropical convergence zone. Southerly winds on the eastern sides of these troughs were present as far south as about 15°N. Maximum day-time potential temperatures

approached 40°C as far north as 30°N, and with the second depression, maximum potential temperatures reached 45°C at 25°N. Temperatures exceeding 40°C are observed in Cairo on an average of two days in each of the months May and June.[25] Along the coast ahead of each depression temperatures in the easterlies remained mostly in the mid-20s, leading to a strong temperature contrast with the southerlies and the development of a coastal front.

At 500 mb the flow was dominantly westerly with small-amplitude troughs and ridges moving eastwards. On each chart the surface depression was found to lie near or just ahead of a trough axis where it crossed the coast.

To illustrate changes in surface weather near and to the south of the desert depressions, Figure 2 gives 3-hourly sequences of pressure and winds at Gialo and Kufra (G and K in Figure 3). For times other than 12 GMT, pressures have been corrected for diurnal variation by using mean differences between pressures at 12 GMT and at other times. Means for May 1962 were used. At Gialo, the reversal from southerly winds ahead of the first depression to northerlies in its rear is well shown. The backing through east at 12 GMT on the 29th suggests the centre passed south of the station. North to north-

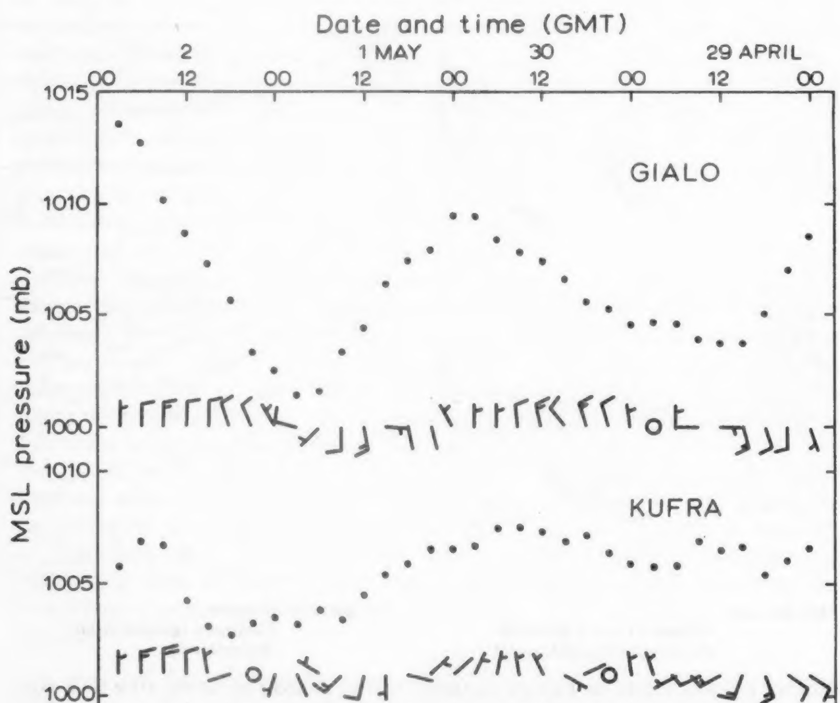


FIGURE 2—SEQUENCES OF 3-HOURLY OBSERVATIONS OF PRESSURE AND WIND AT GIALO AND KUFRA FOR THE PERIOD 29 APRIL TO 2 MAY 1962

● Pressure

west winds are at first light, probably as a result of increased friction following development of the night-time temperature inversion. With the passage of the ridge between the two depressions, winds decreased and then reversed direction to south-easterly before increasing again ahead of the second depression. A veer to north-west late on the 1st suggests the centre passed north of the station.

At Kufra, the pressure trace is more complex. The first dip appears double but this may be unreal because of uncertainties in the corrections for diurnal variation. With both depressions, southerlies are followed by spells with light and variable winds, corresponding to the passage of cols south of the centres. The veer in direction between the northerlies of the 30th and southerlies of the 1st was associated with the eastward passage of an anticyclone north of Kufra. By 12 GMT on the 2nd, good northerlies had set in again with a sudden rise of pressure, showing the passage of a cold front.

To illustrate in more detail the lower tropospheric structure of the second depression, Figure 3 gives the flow patterns at 850 and 700 mb for 12 GMT on 2 May 1962. At 850 mb, a trough extended northwards from the low-latitude easterlies and the centre was still present, but displaced a little north compared with the surface. Southerlies on its eastern side were reported as far south as 10°N. At 700 mb there was little evidence for a closed centre; rather there was a trough in the westerlies just west of Tobruk — in much the same place as the trough at 500 mb, but at 700 mb it was more clearly defined. The trough extending northwards from low latitudes was no longer present, nor were extensive southerlies. Instead, the subtropical anticyclonic belt at about 15°N had two cells, with a col lying above the region of light southerlies at 850 mb. The latitude of the axis of this anticyclonic belt decreased with

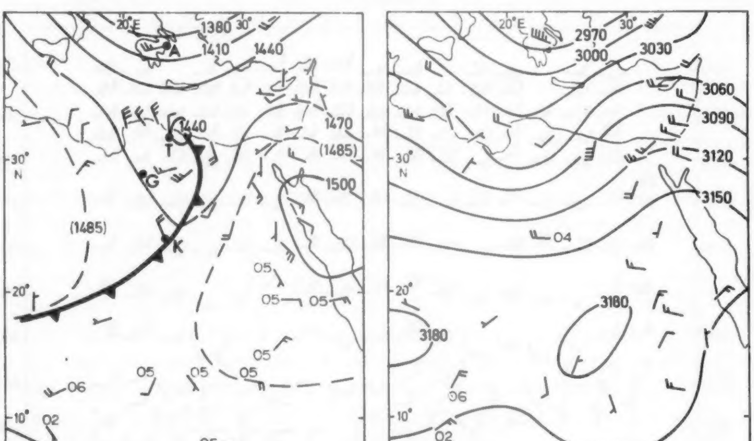
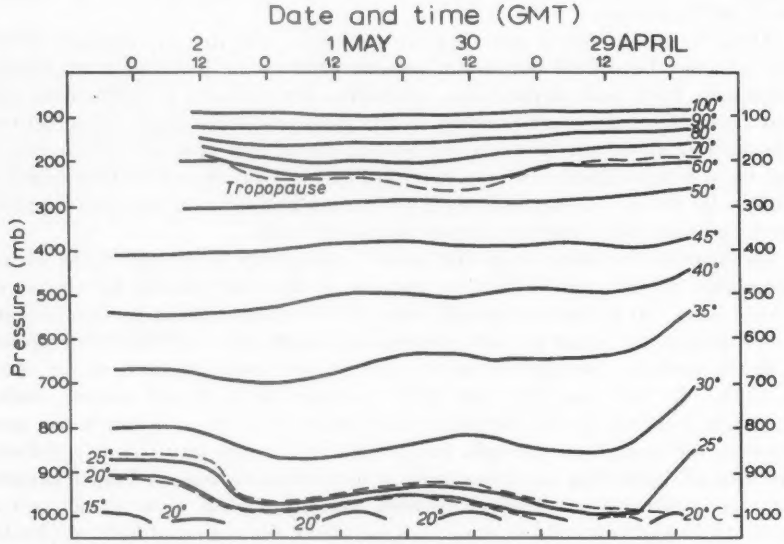


FIGURE 3—CONTOUR CHARTS FOR 12 GMT ON 2 MAY 1962 AT 850 mb AND 700 mb

Letters A, G, K and T indicate positions of Athens, Gialo, Kufra and Tobruk referred to in text. Contours in geopotential metres.

altitude — from over the Mediterranean at the surface, through 30°N at 850 mb, to near 10°N at 500 mb.

Part of the Tobruk time-section is given in Figure 4; it extends from 00 GMT on 29 April to 00 GMT on 3 May and temperatures have been converted



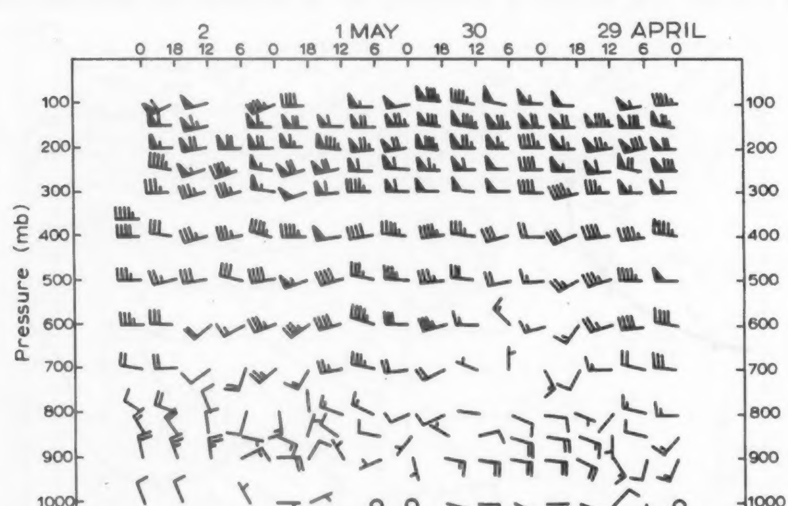


FIGURE 4—VERTICAL TIME-SECTION AT TOBRUK FOR THE PERIOD 00 GMT ON 29 APRIL TO 00 GMT ON 3 MAY 1962 SHOWING POTENTIAL TEMPERATURES BASED ON TEMPERATURES MEASURED BY RADIOSONDE AND WINDS MEASURED BY RADAR

The depth of the inversion near the surface is shown by two pecked lines.

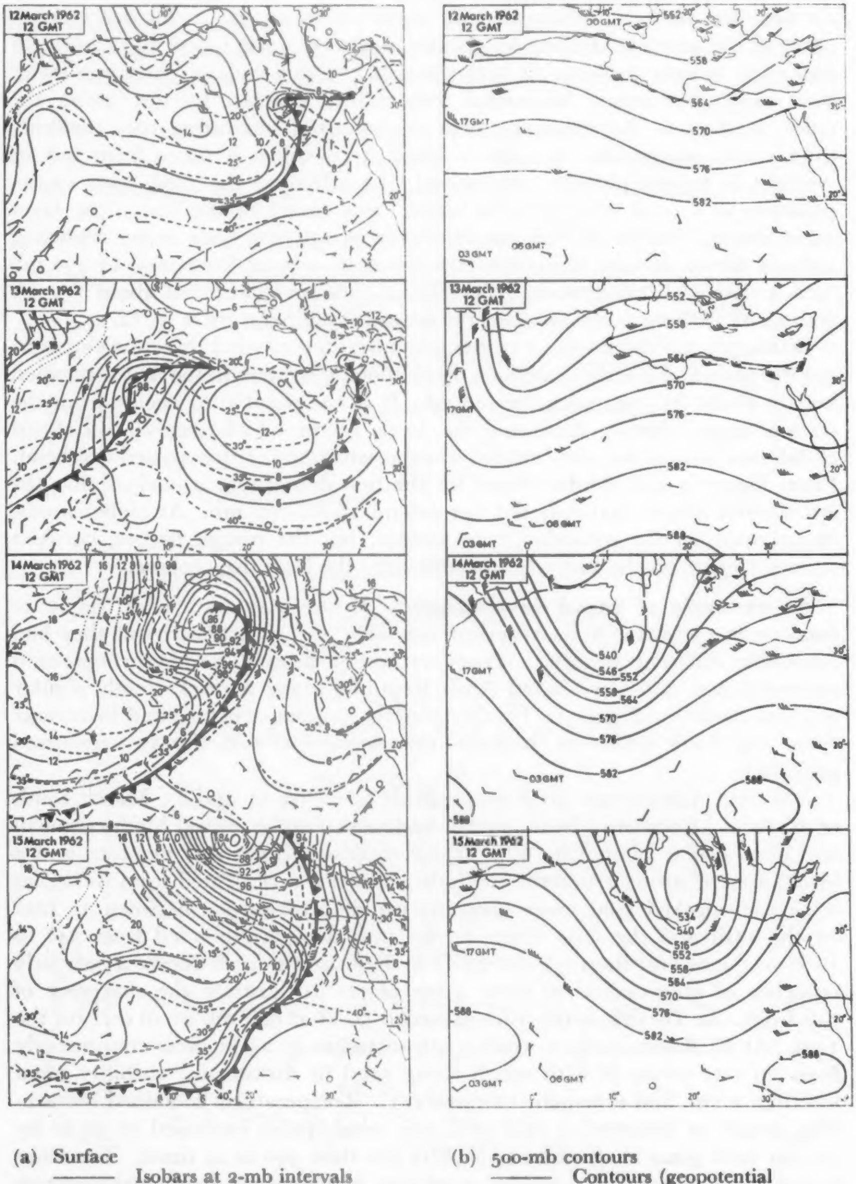
to potential temperatures. A prominent feature is the shallow layer of cool air near the surface, surmounted by an inversion about 50 mb deep. With onset of the north-westerlies, by 00 GMT on the 3rd, the top of the cool layer had risen to near 900 mb. It is the presence of this shallow 'maritime layer' that causes the strong horizontal temperature contrast by day along the coast, leading to the formation of a coastal front separating cool easterlies from warm southerlies. In some respects it resembles a warm front but its position is topographically determined. In addition, the cool layer causes pressures at coastal stations to be higher than would be the case if the layer were absent, thereby leading to difficulties in analysis since many reporting stations are on or near the coast. For example, a layer from 1000 to 950 mb with a potential temperature 25°C gives a pressure increase of about 1·5 mb compared with an occasion when the potential temperature is 35°C.

Below 700 mb there were considerable variations of wind direction throughout the period. Easterlies extended up to about 750 mb with the first depression and to about 850 mb with the second. It is not possible to decide from the section alone whether these are the levels above which there is no closed circulation, or whether they are the levels at which the centres passed overhead. From Figure 3 and similar charts for the first depression, it is clear that the circulations almost certainly did not extend above 700 mb. At higher levels, disturbances in the westerlies were weaker, but the trough passing between 12 and 18 GMT on the 2nd was traceable into the high troposphere.

An example of rapid development. Figure 5 shows a chart sequence from 12 to 15 March 1962. Again there were two disturbances but they had markedly different histories. From 11 to 13 March, a desert depression crossed Libya and the United Arab Republic along a track closely similar to those shown in Figure 1. Furthermore, in general structure and behaviour there was little difference between this depression and the two discussed previously.

A second disturbance developed quickly between 12 and 13 March south of the Atlas Mountains. By the 14th it had moved to the central Mediterranean and deepened to about 980 mb. Its circulation became very vigorous and a broad area of strong southerlies with duststorms was separated from westerlies by a well-marked cold front sweeping rapidly eastwards. Between 12 GMT on the 14th and the same time on the 15th, temperatures fell from 34° to 18°C at Gialo and from 33° to 20°C at Kufra. Figure 6 shows a 3-hourly sequence of observations at these same places to illustrate the sharpness of this front. At Tobruk, southerlies exceeded 50 kt at 900 mb at 18 GMT on the 14th. At El Adem, surface south-south-easterlies at 25 kt blew continuously from 10 GMT onwards with much rising sand or duststorms, visibility often less than 2 km, and dew-points around 0°C. Temperatures remained remarkably steady at between 24 and 27°C but wind speeds increased to 30 kt by 21 GMT with gusts to 44 kt and visibility less than 500 m at times. The front passed at 2320 GMT with a sudden wind veer to westerly, a temporary decrease of speed and a temperature fall of 5 degC in the following hour, but by 10 GMT on the next day wind speeds were again 30 kt or more with visibility below 200 m at times, and the sun was unable to cast shadows until 0830 GMT.

Upper troughs and surface disturbances. Each of the 14 desert depressions crossing north-eastern Africa from January to June 1962 was



(a) Surface
——— Isobars at 2-mb intervals
– – – Potential temperature (°C)

(b) 500-mb contours
——— Contours (geopotential decametres)

FIGURE 5—SEQUENCES OF 12 GMT CHARTS FOR THE PERIOD 12–15 MARCH 1962

International symbols are used for plotting the winds.

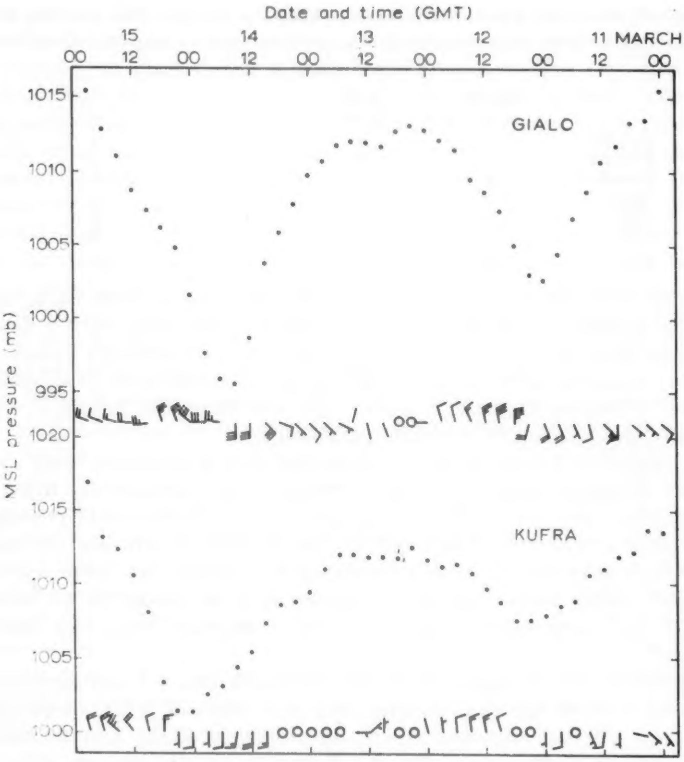


FIGURE 6—SEQUENCES OF 3-HOURLY OBSERVATIONS OF PRESSURE AND WIND AT GIALO AND KUFRA FOR THE PERIOD 11–15 MARCH 1962

● Pressure

associated with a shallow trough in the upper westerlies. For 12 of them the trough axis passed Tobruk on either the same day as, or the day following, the passage of the desert depression; for the remaining 2 the delays were two and three days. During the same six-month period there were 17 further troughs that were not associated with desert depressions. However, 9 of them were preceded by definite surface cold fronts (including the front on 14 March). On 6 of these 9 occasions the trough axis passed Tobruk on either the same day or the day following the passage of the front. For the 3 remaining fronts the delay was two or three days. Of the 8 troughs with which neither a desert depression nor a surface cold front could be identified, 2 occurred in early January and 3 in late June, at times when desert depressions are unlikely to have been present.

Table I shows that the cold fronts unaccompanied by desert depressions were most frequent during the first half of spring. Even though cold fronts could be recognized easily over the land, this was not always so over the sea, particularly when a cool, maritime layer persisted near the surface. This difficulty in analysis tended to increase during the season as the airstreams became potentially warmer than the sea surface. In such a situation a front

TABLE I—NUMBER OF TROUGHS CROSSING TOBRUK AT 500 mb DURING JANUARY TO JUNE 1962, AND THE NUMBERS ASSOCIATED WITH DESERT DEPRESSIONS OR COLD FRONTS

	Desert depressions	Cold fronts	Neither	Total
January	1	1	2	4
February	1	2	1	4
March	3	4	1	8
April	4	1	0	5
May	2	1	1	4
June	3	0	3	6
Total	14	9	8	31

might ride over the maritime layer. On the other hand, there were occasions when the passage of a front was represented by little more than a deepening of the maritime layer in association with the onset of northerly winds. There were also occasions when a front could be traced northwards to a disturbance over the Mediterranean or Europe; this was most likely with a vigorous upper trough preceded by a well-marked front.

The passage of a cold front was often clearly defined as far south as 20°N. At lower latitudes analysis was more difficult, but occasionally fronts could be traced into the intertropical convergence zone which would consequently be displaced southwards, sometimes by five degrees of latitude. By contrast, warm fronts were almost always diffuse except where they were represented by coastal fronts separating, for distances of some hundreds of kilometres ahead of each depression, warm and dry southerlies from cool and moist easterlies.

A cold front seldom appeared to trail westwards into a following depression. Each front marked the leading edge of a new burst of polar air penetrating the tropics. At low latitudes, where the direction of the east to north-east trade winds was often only slightly disturbed by the passage of a desert depression, the arrival of a front was typically associated with an increase in speed and perhaps a slight backing of direction. Changes were more in the nature of pulses in the trade with little or no tendency for southerly components to develop ahead of them.

On 21 March, a wave disturbance moved north-eastwards along a vigorous cold front over Cyrenaica. It was associated with widespread duststorms, the worst of the season at El Adem, where surface winds reached 50 kt in gusts, visibility was reduced to 100 m and the haze top was observed from aircraft to be near 4 km above the ground.

Clouds and rain. Clouds accompanying the desert depressions during 1962 were largely confined to upper levels. Medium clouds were characteristically chaotic, appearing in one or more layers with much altocumulus castellanus. Bases were usually above 600 mb and often above 500 mb. Their horizontal distribution was related to the flow pattern at 500 mb, clouds often appearing in bands or sheets ahead of an upper cold trough and above the surface depression. Sometimes the southern extremity of a medium-cloud system would be at a latitude greater than that of the depression centre, when the approach and passage of a depression would be cloudless, or with only cirrus or cirrostratus. With the larger and more vigorous cold troughs, medium clouds extended as far south as 20°N and sometimes linked with clouds south of 15° or 10° N associated with the intertropical convergence zone.

Development of virga and extensive glaciation typically accompanied medium-cloud masses, but precipitation more intense than 'scattered drops' rarely reached the ground, presumably because evaporation was so effective in the deep layer of dry air between cloud base and the ground. There was circumstantial evidence for such evaporation in the presence of (a) extensive and deep virga not reaching the ground, (b) small-scale, erratic pressure fluctuations of about one millibar, (c) gusty surface winds with variable directions. Sometimes, measurable amounts of rain fell, even with thunder, as at Gialo during the afternoon of 1 May. Such rains were unusual south of 30°N and rare south of 25°N. Apparently complete glaciation of the medium cloud led to either sheets of altrostratus with a variable density or to extensive patches of dense cirrus. The few reports of cloud tops from aircraft were mostly of between 400 and 250 mb, but cirrus or cirrostratus was sometimes present at altitudes, measured or estimated, near 200 mb.

In the maritime layer, there were sometimes some shallow stratocumulus clouds along the coast, but day-time heating dispersed this cloud if it spread inland. Between the surface cold front and the axis of the following upper cold trough, the maritime layer often increased in depth, allowing the development of cumulus, especially over land by day, but such clouds became deep enough for the growth of showers only near the axis of vigorous cold troughs. Even then, showers were usually confined to the coast, and occurred particularly when winds had veered north of west behind the trough axis. Sometimes small cumulus clouds were reported as far south as Kufra. On the few occasions when closed vortices, or cold pools, in the middle and upper troposphere penetrated as far south as 30°N, showers and thunderstorms became heavy and widespread along the coast, and were not confined to daylight hours.

Discussion. The fact that each of the 14 desert depressions lay beneath, or just ahead of, a shallow trough in the westerlies at 500 mb suggests a connection between the two types of disturbance. Tantawy,[24] using composite charts for khamsin days in March of three years, found the surface depression lay farther east, nearer the ridge axis. Petterssen[26] has discussed the relation between positive vorticity advection in advance of upper tropospheric troughs and cyclogenesis in the lower troposphere. Each desert depression lay below part of its associated upper trough where positive vorticity advection is to be expected, suggesting strongly that such advection is a factor in the development of desert depressions. However, cyclonic development at the surface also depends on the thermal field in the lower troposphere. This latter is represented well by the field of surface potential temperature, for when convection extends from the ground through a layer to 850 or 700 mb then the surface potential temperature will be little more than the potential temperature throughout that layer. Such is the situation over north Africa on most occasions at 12 GMT, but not over the sea when a maritime layer of cool air is present at the surface.

Figures 1 and 5 show that the surface potential isotherms form a wavy pattern of cold troughs and warm ridges superimposed on an essentially east–west alignment with colder air to the north. Each desert depression is associated with a warm ridge, and a cold trough extends southward in its rear. The thermal advection field, as represented by these isotherms and by

the isobars, favours cyclogenesis ahead of each centre, and anticyclogenesis in its rear, leading to an eastward movement. Moreover, that part of the cyclogenesis associated with positive thermal advection ahead of the centre is likely to be much greater than the cyclogenesis associated with upper vorticity advection. This is because the first part will be large in the region of strong thermal gradients, whereas the latter will be small since wind speeds (and vorticities) will be weak compared with thermal wind speeds. Now, it is observed that a desert depression moves in a quasi-steady state, with little or no intensification and a retention of its configuration of isobars and isotherms, despite persistence in a region favourable to cyclogenesis due to upper positive vorticity advection. It is likely, therefore, that there is a mechanism which prevents the continued distortion of the thermal field that is expected with continued cyclogenesis. Such a mechanism is non-adiabatic heating and convective mixing within the northerly winds behind a depression. It is here that the warming of the lower troposphere as it flows from sea to land will reduce the rate of advection of isotherms, with the result that distortion of the isotherms is less than that which might have been expected from advection alone, and a brake is placed on the rate of development. This brake is applied diurnally, therefore a diurnal oscillation in the rate of development is possible. With only one surface analysis each day, such an oscillation could not be verified in this study.

A likely structure for the maintenance of a desert depression that emerges from these considerations is of a trough in the upper westerlies overlying a region with a strong meridional temperature gradient. This gradient has been associated with the coolness of the Mediterranean in contrast to north Africa, even to the extent of postulating the existence of a 'Mediterranean front'[20] or a 'subtropical front'.[27] But the contrast of surface temperatures is observed to increase to a maximum in late spring, by which time the incidence of desert depressions is decreasing. This increase is illustrated by Table II which gives monthly means of sea surface temperatures in the square

TABLE II—COMPARISON OF MONTHLY MEAN TEMPERATURES AT THE SURFACE

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
						degrees	*Celsius*					
Sea surface in square 32–33°N 24–25°E	17	16	16	17	19	22	25	26	25	24	21	19
Daily maximum at Gialo (29° 02′N 21° 34′E 61 m ASL)	20	22	26	30	35	38	37	37	36	33	27	22
Difference	3	6	10	13	16	16	12	11	11	9	6	3

Sea temperatures from the atlas of the Royal Netherlands Meteorological Institute,[28] and Gialo temperature from Fantoli.[29]

32–33°N 24–25°E, and of daily maximum temperature at Gialo, where advective cooling from the sea is almost certainly small. At higher levels, there are no observations in the desert south of Tobruk, but it is instructive to consider temperature differences between Tobruk and Athens (A in Figure 3), about 700 km apart and close to the 24°E meridian. Table III shows monthly means for 850 and 750 mb. For the period February to June, the difference for both levels is greater than about 4 degC; November is the only other month with a comparable difference. Considering 850 mb, the seasonal variation in this temperature difference suggests the north–south movement of a latitudinal belt of maximum meridional gradient across the

TABLE III—COMPARISON OF MONTHLY MEAN TEMPERATURES AT 850 mb AND 700 mb

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
						degrees	*Celsius*					
850 mb												
Athens	0·9	1·8	2·5	6·2	11·1	14·5	16·4	17·2	13·1	9·9	5·6	2·4
Difference	3·5	4·1	4·7	5·3	3·9	4·3	2·7	2·2	3·8	3·8	4·3	3·5
Tobruk	4·4	5·9	7·2	11·5	15·0	18·8	19·1	19·4	16·9	13·7	9·9	5·9
Difference	1·3	1·9	4·1	4·3	5·6	4·5	3·7	3·5	4·7	4·9	2·7	1·5
Gialo (estimated)	5·7	7·8	11·3	15·8	20·6	23·3	22·8	22·9	21·6	18·5	12·6	7·4
700 mb												
Athens	−7·4	−6·2	−5·9	−3·0	−0·7	4·1	6·5	7·1	4·3	1·4	−2·6	−5·4
Difference	3·9	3·8	4·5	4·9	5·4	4·1	3·6	3·2	3·1	2·5	3·8	3·9
Tobruk	−3·5	−2·4	−1·4	1·9	4·7	8·2	10·1	10·3	7·4	3·9	1·2	−1·5

Data from tabulations of the World Meteorological Organization;[30] Gialo estimates based on surface data,[29] assuming a constant altitude of 1·50 km for the 850-mb level — probably correct to within 0·02 km.[1]

eastern Mediterranean — northwards in spring and southwards in autumn — and this suggestion is supported by the patterns of 850-mb isotherms over north-east Africa in January, April and July given by Thompson,[1] even though these latter are based on scanty data from the Nile valley and from north-west Africa. Such a seasonal movement of the isotherms is to be expected in association with the well-known seasonal changes of hemispheric circulation patterns, and must be considered to be partly of dynamic origin. Maximum meridional gradients over the Mediterranean are therefore observed in April and November. In April and following months, the meridional gradient over north-east Africa, being south of the Mediterranean, will be less than the maximum. By contrast, in March, and possibly also in February, the belt of maximum gradient should be over north-east Africa. Thus, in so far as seasonal changes of the hemispheric circulation control the meridional temperature gradient over north-east Africa, desert depressions would be expected to be most frequent in March.

There is still the more local effect of differential heating of land and sea to be considered. In the absence of temperature soundings south of Tobruk, an estimate of 850-mb temperatures can be made using afternoon maximum air temperatures near the ground, and assuming a dry adiabatic lapse rate from the ground to 850 mb. At Gialo, for example, this is almost certainly a reasonable assumption in all months, except perhaps January. Table III gives temperatures at 850 mb over Gialo estimated in this way, from which it is seen that the difference between Gialo estimates and Tobruk measurements increases to a maximum in May. This displacement of the timing of the maximum by two months can be ascribed to an increasing differential heating from March to May over-compensating the reduction in gradient caused by the northward movement away from north-east Africa of the belt of maximum gradient associated with changes in the hemispheric circulation. From January to March, the rapid increase of gradient over north-east Africa is attributable to the two processes working together. That differential heating between land and sea plays a part in the development of desert depressions is further supported by the similar depths of the layers in which cyclonic circulation and overland convection occur. Moreover, the baroclinicity in April has been shown[31] to lie mostly below 850 mb.

Tables II and III show that substantial gradients persist into the summer at both the surface and 850 mb, although temperature contrasts at the surface are greatly increased by the presence of the shallow maritime layer over the sea. The almost complete absence of desert depressions in that season is therefore likely to be related to a reduction in the frequency of occurrence of

areas of positive vorticity advection aloft. During the summer, upper troughs do not extend southwards as far as in the spring, an occurrence related to the seasonal northward migration of the axis of subtropical anticyclones at 500 mb — from near 10°N in January to near 25°N in July.[1,32] This northward movement is likely to be most rapid in late May or early June when there is a correspondingly rapid movement of the subtropical jet near 200 mb to about 40°N.[33,34]

Desert depressions are often observed to form over southern Tunisia or north-western Libya, or to intensify in the same region having previously moved eastwards as diffuse centres or open troughs close to the southern side of the Atlas Mountains. Surface pressure falls in this region have been shown[24] to accompany cyclonic vorticity at 500 mb. It is in this region of formation or intensification that lower tropospheric air can first stream southwards in the rear of a disturbance. Farther west, the Atlas Mountains are a barrier to such flow and they probably restrict the advective distortion of the thermal field which is observed to occur more freely to the east.

A model desert depression. The considerable similarities of structure and movement shown by the desert depressions of spring 1962 make it possible to construct a model that can be supported by qualitative physical and dynamical arguments (Figure 7). Ahead of a shallow upper cold trough in the westerlies, positive vorticity advection induces cyclogenesis at the surface,

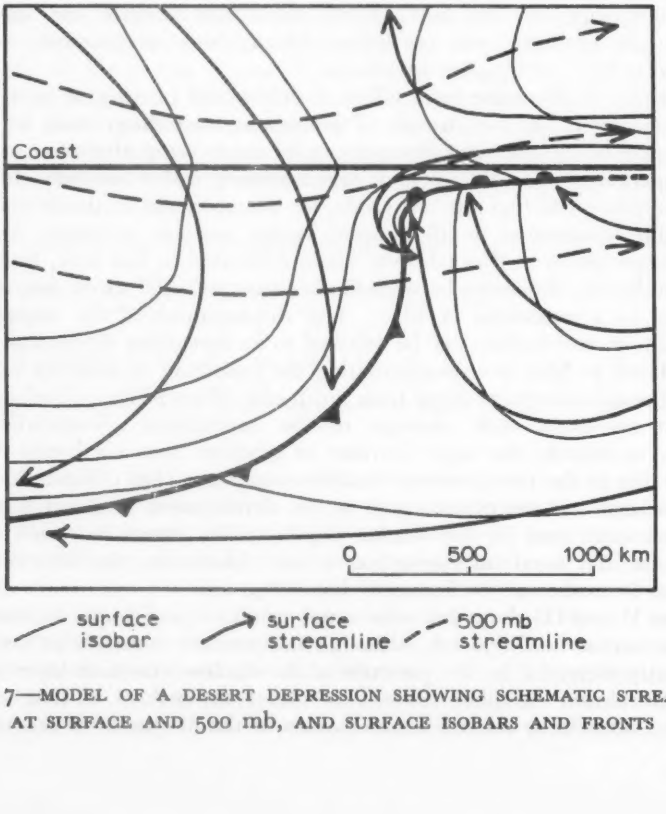


FIGURE 7—MODEL OF A DESERT DEPRESSION SHOWING SCHEMATIC STREAMLINES AT SURFACE AND 500 mb, AND SURFACE ISOBARS AND FRONTS

leading to a northward-pointing trough in the trades, moving eastwards with the upper trough, i.e. against the surface wind. The resulting distortion of the lower tropospheric thermal field leads to increased development and the appearance of a cyclonic centre at the tip of the warm ridge, especially when the coastal temperature contrast is strong. This centre moves eastwards across the desert, along a track some hundreds of kilometres south of the coast, in a direction normal to the broad-scale temperature gradient. It maintains a steady state, perhaps because non-adiabatic effects resulting from differential heating counterbalance advective distortion of the thermal field, and the field of thermal advection remains essentially symmetrical about the axis of the warm ridge. Continued intensification is likely if there is increased positive vorticity advection aloft ahead of a developing upper trough; a turning of the track to the left, to cross the Mediterranean, is then likely. A cold front extends southwards from the centre, and it can sometimes be tracked into the intertropical convergence zone. Its northern part is usually well defined and on occasions can be identified as a southern extension of the cold front associated with a disturbance at higher latitudes. There is no warm front, although a strong coastal front is present ahead of the cyclonic centre, especially in the warmer months. In so far as subjective analyses allow, it is found that the cold front often coincides with the axis of the warm ridge in the surface potential isotherms — warm advection occurs ahead of it, and cold advection in its rear. The front is a particular form of the 'advection discontinuity' discussed by Kirk.[21,22] Moreover, with the dominance of thermal advection in controlling cyclogenesis, it is likely that the direction of vertical motion is closely related to the sign of thermal advection, i.e. upward motion will occur ahead of the front, and downward in its rear. This vertical motion must be expected to change the vorticity at higher levels, but it remains unresolved to what extent the trough at 500 mb, as observed near a steady-state desert depression, is a product of, or the originator of, the circulation.

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A NOTE ON THE COMBINATION OF OBSERVATIONS OF UNEQUAL ACCURACY

By B. R. MAY and K. H. STEWART

Summary. The combination of observations of a variable made with instruments of differing accuracy is considered and it is argued that when the instrumental accuracy is much greater or much less than the natural variability, standard textbook results are applicable. The less familiar case, when the instrumental accuracy and the natural variability are comparable is discussed and an iterative procedure for calculating the best estimate of the mean and its variance in these circumstances is given.

If we make several observations of a quantity, they are not usually all the same, either because there are errors in the measurements or because the quantity itself is not constant, or both. The simplest method of combining the observations is to take their arithmetic mean, and in many cases this gives the best possible estimate of the quantity that can be made from the observations. If, however, some of the observations are known to be more accurate than others because they were made by better observers or with better instruments, for example, it is obvious that they should be given greater weight; it is shown in textbooks on statistics that the appropriate weighting factor is $1/V_j$, where V_j is the variance of the jth observation (the square of the standard error).

It is not usually emphasized that the V_j to be used in these weighting factors are the variances of the *observations* not the variances of the *measurements*, that is to say they are the sums of the variances due to instrumental (or observer) error, V_i, and the variance due to the natural variability of the quantity being observed, V_0. In laboratory physics it is common for V_0 to be very small compared with the V_i so that $V_j \approx V_i$ and weighting of observations according to $1/V_i$ is appropriate, but in outdoor physics the variability of the phenomenon, measured by V_0, is often much greater than the error of the measurements, the V_i. In this case the use of $1/V_i$ as weighting factors (instead of the correct values $1/V_j = 1/(V_i + V_0)$) can give absurd results. For example if we were finding a monthly mean temperature from a set of daily readings and the readings on one day happened to be taken on a precision laboratory thermometer with an accuracy of 0·001 degC it would be absurd to give those readings 10^4 times the weight of the readings on the other days, taken with a thermometer accurate to, say, 0·1 degC. In cases where the natural variability (V_0) is much greater than the instrumental errors (V_i) it is far better to give all observations equal weight.

We can summarize the two extreme cases as follows :

Case 1. Natural variation large, all instrument errors small, $V_0 \gg V_i$.

$$\text{Weighting factor } \frac{1}{V_i + V_0} \approx \frac{1}{V_0} \text{ (equal weights).}$$

Case 2. Natural variation small, instrument errors large, $V_0 \ll V_i$.

$$\text{Weighting factor } \frac{1}{V_i + V_0} \approx \frac{1}{V_i}\,.$$

We have recently had to deal with some observations which fell into an intermediate category. The accuracy of individual observations (which could be estimated from internal evidence) covered quite a wide range and the natural variability of the quantity being studied lay in the same range. We could find no discussion of how to handle this type of data in the textbooks and would like to report on the method we have developed.

We assume we have a set of observations $x_1, x_2, x_3, \ldots x_i, \ldots x_n$ and that the 'instrumental' accuracy of each observation is known and is expressed by the variance V_i (that is, V_i is the variance that would be obtained for a series of observations made with the ith instrument on an unchanging quantity x). We wish to make the best estimate we can (M_e) of the mean value (M)

of the quantity x, recognizing that x may have a natural variability expressed by its variance, V_0, whose value is not known. There is no difficulty in writing down the value of M_c; it is the weighted mean

$$M_c = \frac{\sum\limits_n \frac{x_i}{V_i + V_0}}{\sum\limits_n \frac{1}{V_i + V_0}}. \qquad \ldots (1)$$

The difficulty is to find a value of V_0 to use in this expression. If we assume for the moment that the true mean value of x, M, is known, then it can be shown that the best estimate (V_0') of V_0 is given by

$$V_0' = \frac{\sum\limits_n \frac{(x_i - M)^2 - V_i}{(V_i + V_0)^2}}{\sum\limits_n \frac{1}{(V_i + V_0)^2}}. \qquad \ldots (2)$$

(This expression can be derived either by maximizing the probability of obtaining the set of observations $x_1, x_2, \ldots x_n$ with respect to V_0, or by considering that each observation provides an estimate of V_0 and combining these estimates with appropriate weights.)

We have not been able to solve equations (1) and (2) except by an iterative computer process, but the programme needed is simple and converges rapidly. It is assumed initially that $V_0 = 0$, and equation (1) is used to evaluate M_c. This value of M_c is used as an estimate of M in equation (2) (still with $V_0 = 0$ on the right-hand side of the equation) to evaluate a value of V_0, which is then used as a better approximation to V_0 in equation (1) to start a new iteration. The process stops when successive values of M_c and V_0 differ by an acceptably small amount, and these values are taken as the best estimates of the mean value and the natural variance of x. The only difficulty in the operation of the programme is that it may produce negative values of V_0, which are physically unacceptable. This is to be expected if V_0 is small (if $V_0 = 0$, then equation (2) will yield negative values as often as not, through the statistical distribution of the instrumental errors) and in fact if equation (2) yields a negative value then the best estimate that can be made of V_0 is that it is zero.

The accuracy of the final estimate of M, M_c, is measured by its statistical standard deviation S_c, which can be shown to be given by

$$S_c = \left[\sum_n (V_0 + V_i)^{-1}\right]^{-\frac{1}{2}}$$

This, of course, reduces to the usual expression $S = (V/n)^{\frac{1}{2}}$ if all observations have the same variance, V.

The methods given here for estimating the mean value of x can fairly easily be extended if it is required to find the best regression equation between x

and some other variable, assuming that the instrumental errors, V_i, are known and that some reasonable assumption can be made about the way in which the natural variability, V_0, varies with x.

The programme just outlined has been used to calculate means (and their standard deviations) and the 'natural' variance for groups of observations of molecular oxygen densities in the thermosphere made by the Meteorological Office equipment in the ARIEL 3 satellite. The results seem reasonable, but the question may be asked whether they are any better than results obtained by taking simple arithmetic means or, if instrumental errors are thought to be large, means weighted according to the method of Case 2. It has been shown by considering limiting cases and by computer simulations that, on average, results by the method described here will be closer to true values than results by the other two methods, but in general the improvement will not be very great. The maximum gain over the better of the two simple methods is only about 15 per cent (that is, a 15 per cent reduction in the spread of estimates of M that would be obtained if the sets of observations were repeated many times), but in practice it is not always easy to see which of the two simple methods is appropriate and, if the wrong one is chosen, worse errors will result. The procedure described here avoids the need for this choice, and is worth using in any doubtful cases as well as in other cases when it is deemed necessary to squeeze the last drop of accuracy from the measurements.

REVIEWS

Numerical weather prediction, by G. J. Haltiner. 233 mm × 160 mm, pp. xvi + 317, *illus.*, John Wiley and Sons Ltd, Baffins Lane, Chichester, Sussex, 1971. Price: £5.

Now that numerical weather prediction is no longer an esoteric research project but is an operational routine which in mid-latitudes at least is a basic forecasting tool, it has become part of the general education of meteorologists and some account of it must appear in any reasonably advanced meteorological syllabus. We might expect a number of textbooks to be available for students, and their elders, written by those who give courses, but so far there have been very few, probably more in Russian than in English, and fewer still of any quality. Professor Haltiner has written a book aimed particularly at students and scientists who need to have a general view of the basic ideas, and it is sure of a welcome as a pioneer effort offering a connected account.

The author has many problems to overcome. Perhaps the first is that the subject matter — numerical weather prediction — of necessity requires the use of a lot of mathematics and it would be very easy to allow the mathematics to dominate so that the reader becomes more involved in following a mathematical argument than considering the physical processes of meteorology. There are, of course, parts of the book devoted to mathematical problems, those of computational stability and methods, but in the main development the author has managed to keep the meteorology well in focus, so that this is not essentially a mathematical book although there is an abundance of equations.

The second main problem is what to include. There is a vast literature dating from the late 1940s and it would be impossible to attempt to pay

attention to it all. The earlier work was mainly concerned with vorticity models which have pedagogic attraction because there is a clear physical picture associated with the spin about a vertical axis and it is possible to argue qualitatively and then supply the quantitative analysis. There is probably now little or no research going on anywhere concerned with vorticity models and although routine predictions based on them are still made in a number of countries these models are obsolescent. More recent research and more recently developed models for routine forecasting have used the primitive equations, that is a slight modification of the Navier–Stokes equations and equations relating to supply and distribution of energy. How much space should be allotted to out-of-date methods? Professor Haltiner chooses to devote nearly half of his book to the foundations and the development of vorticity ideas, and this may be right for the student reader although it looks rather a lot in retrospect.

There has been a rapid increase in the number of published papers over the last decade, as more countries have developed expertise in numerical prediction and most of them have been devoted to primitive equation models. The author thus has a problem of selection from all this material for the second half of his book. It is an unenviable problem and the solution is bound to invite criticism. Mine is that the choice does not seem to have been dictated by a pattern which can be clearly seen, and that it tends to be parochial; of course the latter is understandable since the book is probably the outcome of a series of lectures prepared for students at Monterey.

The book has considerable solid merits. Professor Haltiner is known from his previous writings to be extremely clear and lucid and these qualities are apparent throughout. The first half of the book covers the development of the equations, the linearized versions and the possible wave-motions, the elimination of the unwanted motions by filtering and the development of vorticity models. There is a surprising amount of additional information about such subjects as the ancillary mathematics, map projection, integral constraints, etc. The second half contains some material relating to most of the relevant aspects that have to be taken into account in trying to develop realistic atmospheric models. There are accounts of the introduction of physical effects, such as the hydrological cycle, radiation, cumulus convection, of mathematical techniques and of preparing the data on which the predictions are to be made. No particular aspect is dealt with in detail but enough is given to make the problem clear and to indicate one way of dealing with it. Some of the models currently in use in the U.S.A. are also briefly described.

Professor Haltiner's book does not at this time have a serious rival for its intended purpose and it is sure to be popular with students who will readily understand this crisp writing, and by others who have to design and give courses in numerical weather prediction.

E. KNIGHTING

The blizzard of '91, by Clive Carter. 225 mm × 145 mm, pp. 204, *illus.*, David and Charles (Publishers) Limited, South Devon House, Newton Abbot, Devon, 1971. Price: £2·75.

On 10 March 1891 a depression from the south-west deepened rapidly near the Brest Peninsula and moved along the north coast of France. The resulting blizzard affected most of southern England but hit Devon and

Cornwall with especial ferocity, causing much loss of life, damage and disruption of communications. The author has given a detailed reconstruction of the impact on the community, with many contemporary accounts and well illustrated by photographs and some attractive drawings. Two aspects have received particular attention: the casualties in the storm at sea and the stranding of trains in snowdrifts around Dartmoor.

The emphasis is on 'human interest': on efforts to save the shipwrecked (some of whom survived for a time only to succumb to exposure to the severe gales at near-freezing temperatures, within sight of the would-be rescuers); on the trials of stranded passengers (the 'Zulu' express which had left Bristol at 6 p.m. on Monday 10 March did not reach its destination of Plymouth until 8.30 p.m. on Friday 14 March); and on the isolation of farm, hamlet and town. There is some occasional hyperbole in the account, as when winds are described as of hurricane force, but a useful record is provided of the tragedy, destruction and disruption caused by this famous blizzard and will give a basis of comparison with more recent blizzards.

The meteorologist will be glad to find a sequence of weather charts reconstructed from the contemporary British *Daily Weather Reports* in terms of frontal analysis by Mr F. Singleton of the Meteorological Office. These charts show well the frontal contrast between mild south-westerlies over France and the cold north-easterly gales over Devon and Cornwall at the time when the blizzard was developing. On the map on page 192 there are some errors in the values of the central isobars of the depression.

J. E. ATKINS

Satellite and computer applications to synoptic meteorology. Lectures presented during the scientific discussions at the fifth session of the Commission for Synoptic Meteorology (Geneva, 15 June–3 July 1970). 275 mm × 213 mm, pp. xiv + 88, *illus.*, Secretariat of the World Meteorological Organization, Geneva, Switzerland, 1971. Price: Sw. Fr. 15.

This WMO publication reproduces three lectures presented during the scientific discussions at the fifth session of the Commission for Synoptic Meteorology (Geneva 15 June–3 July 1970). The first, available in both Russian and English versions, is 'The use of satellite information for weather analysis and forecast' by A. I. Burtsev and A. D. Čistjakov. Apart from a few unconventional expressions and ambiguities, the English text presents a competent account of the use of satellite data in an operational context. There is evidence throughout the paper of the great importance given to satellite information in the U.S.S.R. and of its influence on the activities of the weather service.

In the operational application of satellite data to synoptic analysis, emphasis is placed on the combined use of television, infra-red and actinometric information to elucidate the three-dimensional structure of cloud formations. In routine applications for the estimation of various meteorological parameters, objective methods are described, these being based for the most part on statistical rules derived from painstaking comparisons over large areas. Some of these data are given in Tables 1 to 4. The authors stress that there is an urgent need for the development of objective methods for the decoding of satellite information by computer and briefly refer to current picture-processing techniques.

Applications to forecasting include the now conventional methods based on the identification of cloud systems and their typical evolution as well as the direct input of derived information into numerical forecasting schemes. No reference however is made to Satellite Infra-Red Spectrometer (SIRS) type data. The paper ends, surprisingly, with an account of an experiment on routine weather forecasting without using data on visual cloud and weather phenomena but using satellite and radar information instead. It is of course more orthodox to regard both satellite and radar information as supplementing rather than replacing conventional types of observations. Yet we read: 'In connexion with the complex automation carried out in the Hydrometeorological Service of the U.S.S.R. the existing network of meteorological stations will be replaced by automatic stations, which will not be able to provide information on the amount and forms of clouds as well as on weather phenomena'.

For those wanting a brief account of the recent U.S. development in the application of satellite data to numerical forecasting, the second paper 'Operational use of SIRS data' by William L. Smith and Edwin B. Fawcett can be warmly recommended for its practical approach. The SIRS was carried on the NIMBUS spacecraft and briefly provides measures of the radiation emitted by the earth and atmosphere in seven narrow spectral intervals of the 15-micrometre carbon-dioxide band and one narrow spectral interval of the 11-micrometre window region. The radiation measured in the various spectral intervals corresponds to a vertically weighted mean temperature of different atmospheric layers. The practical problem is to use the observed radiances to deduce the vertical temperature profile. This paper describes the regression method of doing this, in which use is made of conventional temperature data gathered over a short period of time and updated every few days. These derived temperature profiles can then be used as input for routine numerical forecasting operations. The importance of this development is at once evident and interest immediately centres on the reliability of the method. Accordingly, much of the paper is taken up with a consideration of the advantages and limitations of these data in an operational context.

The last paper, 'An operational system for numerical weather prediction' by L. Bengtsson and L. Moen is an interesting one for all forecasters and can serve as a model for the integrated research/operations activity that should be a feature of all meteorological services. The authors have been successful in giving a well-balanced account of a relatively simple filtered model and its exploitation to best advantage in an operational organization. Of particular interest is the account of a grid-telescoping technique and its advantages in meeting operational requirements. Some pertinent remarks on the relative advantages and disadvantages of filtered and primitive-equation models in operational use will be of interest to most readers.

T. H. KIRK

Meteorological factors in air pollution, WMO Technical Note No. 114, by A. G. Forsdyke. 275 mm × 213 mm, pp. iv + 32, *illus.*, Secretariat of the World Meteorological Organization, Geneva, Switzerland, 1970. Price: Sw. Fr. 10.

This WMO *Technical Note* is described in the foreword as designed specifically for the non-specialist who will from time to time be required to solve problems or provide advice on matters relating to air pollution. Dr Forsdyke admirably

fulfils his aim of producing a simple text, and it will serve as an excellent introduction to the subject for the ordinary meteorologist and non-meteorologist alike.

The note deals with the dispersion of pollutants in the atmosphere and is largely concerned with pollution at the ground over fairly short distances. After a brief opening section in which the main pollutants are mentioned, the author describes the meteorological factors involved (wind, turbulence and stability) in very simple terms for the non-meteorologist. Typical shapes which a plume from a chimney may assume in different stability conditions are illustrated. In the next, and most important, section Dr Forsdyke develops the standard formula for the concentration at a point downwind of pollutant from a single continuous source. There is no pretence that the derivation is rigorous, but the author very cleverly succeeds in taking the veriest novice through the essential steps. If a minor criticism may be made it is that many users of the book will find the elementary derivation of the Gaussian from the binomial distribution unnecessary. Pasquill's* method of deducing stability from wind speed and cloud cover is described, and tables and a worked example are included in an appendix. Enough information is thus included in the note to enable simple queries to be answered. Advice is given on the need for making allowances for sampling time, plume rise due to buoyancy, multiple sources, sloping ground, rough terrain, valleys and sea-breezes; and dependence of stability on air mass and anticyclonic inversions is also discussed. Most of these matters can be dealt with only in a rough subjective manner and the reader should begin to realize that in spite of Dr Forsdyke's extremely simple presentation, the subject is in fact a most complex one. Nevertheless, as an introduction for the non-expert the note can be thoroughly recommended.

M. H. FREEMAN

Meteorological conditions in the Arctic during IQSY. Arctic and Antarctic Research Institute, Transactions, Volume 274, edited by I. M. Dolgin and L. A. Gavrilova. 240 mm × 165 mm, pp. vi + 145, *illus.* (translated from the Russian by Israel Program for Scientific Translations, Jerusalem), Keter Press Ltd, 15 Provost Road, London NW3 4ST, 1971. Price: £4·20.

This book consists mainly of papers giving the results of the investigations carried out in the Soviet Arctic during the IQSY (International Quiet Sun Year). To meteorologists specifically interested in the Arctic the diagrams and tables may be of interest, but the text is mainly narrative, boring and uncritical. The book is evidently written for internal circulation as of the 80 references (excluding the last chapter) only three are to non-Soviet sources, there is neither a map nor a gazetteer giving the position of the observing stations referred to, and several terms used in the text are not defined. The translation is poor and at times wrong and in the opposite sense of what the author must have written. I would not recommend this book to meteorologists for general interest.

R. A. HAMILTON

* PASQUILL, F.; The estimation of the dispersion of windborne material. *Met Mag, London*, **90**, 1961, pp. 33–49.

OBITUARY

It is with regret that we record the death on 14 May 1972 of Mr N. C. Helliwell, Principal Scientific Officer, Met. O. 3.

AWARD

We note with pleasure that the seventeenth International Meteorological Organization Prize for outstanding work in meteorology and in international collaboration has been awarded for this year to Academician Viktor Antonovich Bugaev, Director of the Central Institute of Prognoses in Moscow, by the Executive Committee of the World Meteorological Organization.

CORRECTIONS

Meteorological Magazine, April 1972, p. 107, Table VI, Rule No. 17, Critical anomaly : for '> -6' read '< -6'.
Meteorological Magazine, April 1972, p. 108, Table VII, Period (c) November : for '$N_c - N_m = 0$ or 1' read '$N_c - N_m = 0$'.

OFFICIAL PUBLICATION

The following publication has recently been issued :
Meteorological glossary. Fifth edition. (London, HMSO. Price: £2·75)

This glossary has been revised and enlarged to include a number of new entries and revisions stemming from recent advances made, for example, in numerical prediction and satellite meteorology. Units of the Système International (SI) have been used, though in some cases the traditional British or metric units have been included as well for the convenience of user interests during the period before the complete adoption of SI units.

The new edition is about 10 per cent larger than the fourth edition and includes most of the terms and concepts which are in everyday use in meteorology and many others which are in less common use. In addition, relevant information from mathematics, statistics, physics and geophysics is included.

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